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Global intermodal liner shipping network design

Zhiyuan Liu
Monash University

Qiang Meng
National University of Singapore

Shuaian Wang
University of Wollongong, shuaian@uow.edu.au

Zhuo Sun
Dalian Maritime University

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Abstract

This paper presents a holistic analysis for the network design problem of the intermodal liner shipping system. Existing methods for liner shipping network design mainly deal with port-to-port demand. However, most of the demand has inland origins and/or destinations. Thus, it is necessary to cope with inland origin-destination (OD) pairs involving a change in transport mode from inland transportation to maritime shipping. A method is first proposed to convert inland OD demand to port-to-port demand. Then, a framework for global intermodal liner shipping network design is proposed. Finally, the proposed methodology is applied to and numerically verified by a large-scale network example.

Keywords

network, shipping, liner, intermodal, design, global

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GLOBAL INTERMODAL LINER SHIPPING NETWORK DESIGN

ABSTRACT

This paper presents a holistic analysis and useful software for the network design problem of the intermodal liner shipping system. The existing methods for liner shipping network design mainly deal with port-to-port demand. However, a large proportion of the demand has inland origins and/or destinations. Thus, it is necessary to cope with inland origin-destination (OD) pairs involving a change in transport mode from inland transportation to maritime shipping. This paper first proposes a solution method for the conversion of inland OD demand to port-to-port demand. Then, it presents a framework for global intermodal liner shipping network design. By virtue of the software tool designed, the proposed methodology is applied to a large-scale global shipping network example.

Keywords

Liner Shipping System; Network Design; Destination-based Model; Large-Scale Applications; Intermodal Transport

1. INTRODUCTION

Container trade, which is the fastest-growing cargo segment in world seaborne trade, expanded at an average annual rate of 8.2 per cent between 1990 and 2010. In 2010, container trade volumes reached 140 million twenty-foot equivalent units (TEUs), or over 1.3 billion tons (UNCTAD, 2011). Containers are generally transported by liner shipping companies on regularly serviced ship routes, which also involve container handling operations at loading, discharge or transshipment ports. A liner shipping company (the carrier) announces the schedules and itinerary for its liner shipping service to the customers (the shippers). The customers then decide which liner shipping service to use to transport their containers. Therefore, liner shipping services can be equated with bus services on a road network (Christiansen et al., 2004). Compared with other transportation modes, liner shipping is more secure, cost-efficient and eco-friendly. Rapid globalization has provided great impetus to the growth of container cargo demand in the liner shipping industry. Thus, to cope with the increased demand, liner shipping companies tend to redesign their liner shipping services approximately every three to six months to minimize operating costs and seek higher profits.

For the sake of presentation, a single liner shipping service is termed a *ship route*, and is uniquely decided by (a) the sequence and schedule of sea ports visited, and (b) the type and number of ships deployed on it. Due to its practical significance, the network design of liner shipping routes has attracted much attention from academic researchers. Rana and Vickson

(1988, 1991) and Shintani et al. (2007) designed a single liner ship route without transshipment. Reinhardt and Pisinger (2012) investigated a butterfly ship route design problem where containers can be transshipped from one ship to another. Fagerholt (1999, 2004), Sambracos et al. (2004), and Karlaftis et al. (2009) examined feeder network design problems with one hub port and many feeder ports. Imai et al. (2009) and Gelareh et al. (2010) worked on a hub and spoke liner shipping network design problem with many hubs and many feeder ports. Agarwal and Ergun (2008), Álvarez (2009), Jepsen et al. (2011), and Meng and Wang (2011) studied more general network design problems where the transshipment of containers can occur at virtually any port.

However, all of the abovementioned liner shipping network design studies deal with port-to-port origin-to-destination (OD) pairs, meaning that both the origin and the destination of each OD pair are sea ports. Yet, in practice, most of the cargo demand originates from inland locations. For example, Chicago is not a sea port. If the origin and/or destination of a given OD pair is located inland, then it is termed an inland OD pair. For each inland OD pair, an *intermodal transportation* is required to, first, transport a container from its inland origin to a sea port (by truck, train or barge) and, then, load it onto a liner ship. Thus a mode change is required at the sea port. Herein, any possible location for an origin or destination is termed an *equipment supply point* (EQSP) for the liner shipping company (The company calls it an EQSP because at the origin, the company needs to supply an empty container to the customer, and at the destination, the company needs to collect an empty container or an empty container is supplied to the company). Thus, apart from operating regular maritime liner shipping services between sea ports, a shipping company should also account for transporting inland cargo from its origin to a corresponding export port and then from an import port to an inland destination, using what is known as the *inland network*. Such transportation network design, taking into consideration both maritime liner shipping and the inland network, is termed global intermodal shipping network design.

Compared with designing seaborne liner services alone based on port-to-port demand, intermodal shipping network design is a more practical issue for the liner shipping companies. To the best of our knowledge, how to comprehensively solve the global intermodal liner shipping network design problem is still an open question in the literature due to its strong NP-hardness. Thus, this topic makes considerable theoretical contributions with practical significance.

This paper addresses the network design problem for global intermodal shipping systems by providing a holistic methodology that covers both inland transport expenses and seaborne shipping costs/time. The container cargos are assigned to the best itinerary from their origin EQSP to their destination EQSP, considering the overall transport costs/time, which include (a) inland transportation costs/time, (b) container handling costs/time at loading and discharge ports, and (c) seaborne shipping costs/time. Moreover, to better reflect the real-life conditions, cargos from the same OD pair are allowed to be transported on different itineraries/routes, implying that these cargos would be handled at different ports and shipped via different ship routes. It should be noted that, for the inland transportation, the shipping companies do not usually operate the inland transport services themselves but purchase them from local transport companies (e.g., trucking companies).

To address the global intermodal shipping network design problem, we define the itinerary of a container from its origin to its destination as the *container route*, which includes the inland part and the seaborne part. To design the network, first, a set of container routes is generated incurring minimal costs while fulfilling the transit time constraints. Here we incorporate the practical transit time constraint because customers will be unsatisfied and may change the supplier if the transit time of their containers from origin to destination is longer than an acceptable limit. Then, a logit model is adopted to proportionally allocate the inland OD demand to pairs of loading/discharging ports on the generated container routes, which converts the inland OD demand into port-to-port demand. The network design problem can hence be solved by designing seaborne liner shipping services based on the port-to-port demand. In this paper, a destination-based model is further proposed for the seaborne liner shipping network design.

The contributions of this paper are threefold. First, it provides a comprehensive methodology for the unanswered problem of global intermodal liner shipping network design, in which inland transportation costs, port handling costs and seaborne shipping costs are all considered. Second, for the seaborne shipping network design, a destination-based optimization model is proposed to quantitatively evaluate any set of liner shipping networks. In addition, two heuristic approaches are presented to refine the ship routes and design new ship routes. Third, to improve the real practicability of the proposed methodology, a software tool is designed and tested on a large-scale global shipping network.

2. PROBLEM DESCRIPTION

2.1 Assumptions and Notation

Let W denote the set of all OD pairs for a liner shipping company, and q_w denote the weekly volume of container demand, in TEUs. Let $\overline{W}$ denote the set of inland OD pairs; obviously $\overline{W} \subset W$. Since most of the existing solution methods for liner shipping network design only deal with seaborne port-to-port demand, it is necessary to convert all inland OD demand into port-to-port demand, in order to apply the liner shipping network design methods. Thus, for the cargo of an inland OD pair, its loading port and discharge port need to be determined; this problem is termed gate port allocation (GPA) for ease of presentation. In practice, the cargos of a single inland OD pair may be handled at different loading/discharge ports. For example, part of the demand from Chicago to Hong Kong may be loaded at the port of San Pedro, while the rest may be loaded at Seattle. In such cases, part of the demand for Chicago-Hong Kong is converted into the port-to-port OD pair San Pedro-Hong Kong and the rest to Seattle-Hong Kong.

For a liner shipping company, two concerns should be accounted for in the GPA problem: transit time and transport costs. The transit time and transport costs here cover both the inland part and the seaborne part. Note that inland transportation is usually faster but more expensive than maritime transportation. Thus, the liner shipping company should balance the trade-off between the two parts. A holistic analysis that covers the entire cost and time from inland origin to destination is necessary. Hence, the liner shipping company aims to search for the most cost-efficient container routes that fulfill the transit time constraints. The demand for each inland OD pair is then converted into a loading port and a discharge port that are on one of these cost-efficient container routes. For each inland OD pair $w \in \overline{W}$, the number of cost-efficient container routes is denoted by k_w, and the set of all of these routes by K_w. Let p_k denote the proportion of OD demand allocated to each route $k \in K_w$; then p_k is decided by the following logit model:

$$p_k = \frac{\exp\left(-\theta C_k\right)}{\sum_{l \in K_w} \exp\left(-\theta C_l\right)}, k \in K_w, w \in \overline{W} \tag{1}$$

where C_k denotes the overall transport cost on container route $k \in K_w$, and θ is a positive parameter. For any give path $k \in K_w$, the value of C_k is fixed and flow-independent. It should be noted that the congestion issue on each path is not considered here, because the cargos of only one shipping company are taken into account and weekly demand is usually not very high, meaning that the impact of congestion is marginal. Therefore, the GPA problem becomes a problem of building the set of cost-efficient container routes K_w for each inland OD pair $w \in \overline{W}$.

It should be pointed out that two different container routes in the set K_w may have the same loading and discharge ports. In such cases, the shares of OD demand from these two routes are both loaded onto the same port-to-port OD pair. Before introducing the method for GPA, the networks for inland and maritime transportation will be presented.

2.2 Global Transportation Network

The inland network is built based on existing multi-modal transportation systems, which include three travel modes: rail, truck and barge. The cargo from one inland EQSP to its loading port can be transported by one, two or a combination of all three modes. The network should be built based on the historical data of the liner shipping company. For the maritime network, any two sea ports are supposed to be connected, and the transit time and transport costs between any two ports can be estimated based on historical data.

Combining the inland and maritime transportation networks, we have a comprehensive transportation network that can be used for global shipping network design. Let N denote the set of nodes in the global network, where these nodes include the inland EQSPs $\bar{N}$, the sea ports $\hat{N}$ and the inland transfer nodes $\tilde{N}$. These transfer nodes allow intermodal or intramodal transfers to take place at any inland location. For instance, transporting cargo from Lanzhou, China to its export port in Shanghai may first involve the rail system from Lanzhou to Wuhan, a provincial capital city, and then a barge from Wuhan to Shanghai; thus, Wuhan would be an intermodal transfer node. There may be more than one transportation service between any two nodes. Let A denote the set of links, and let it consist of two subsets: the inland link set $\bar{A}$ and the maritime link set $\hat{A}$. Each link $a \in A$ has a transit time t_a and a transport cost c_a. The values of t_a and c_a are positive constants. For each inland link $a \in \bar{A}$, its travel mode is also recorded. The capacity of each inland link is assumed to be infinite, because the weekly demand between a given inland OD pair is usually not very high and is unlikely to reach the capacity of the fleet operating on the link.

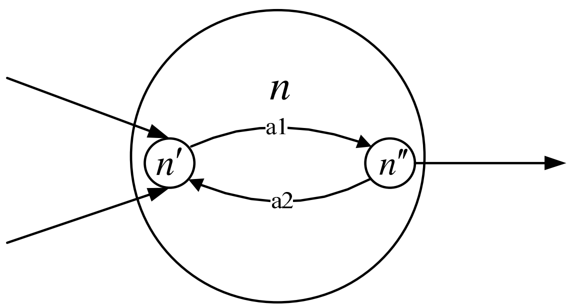

Figure 1 Network representation for Sea Port n

Other than the inland transportation cost and maritime shipping cost, there is another cost involved in container transportation, that is the handling cost at each sea port. In order to cope with the handling cost, a network representation is carried out for each sea port: each sea port node $n \in \hat{N}$ is replaced by an import node n' and an export node n'', as shown in Figure 1. Between n' and n'', two links a_1 and a_2 are defined, as shown in Figure 1, with a_1 the export link and a_2 the import link. These two types of links are also included in the link set A. The values of t_a and c_a connected to these import (export) links are then the time and cost of discharging (loading) one container.

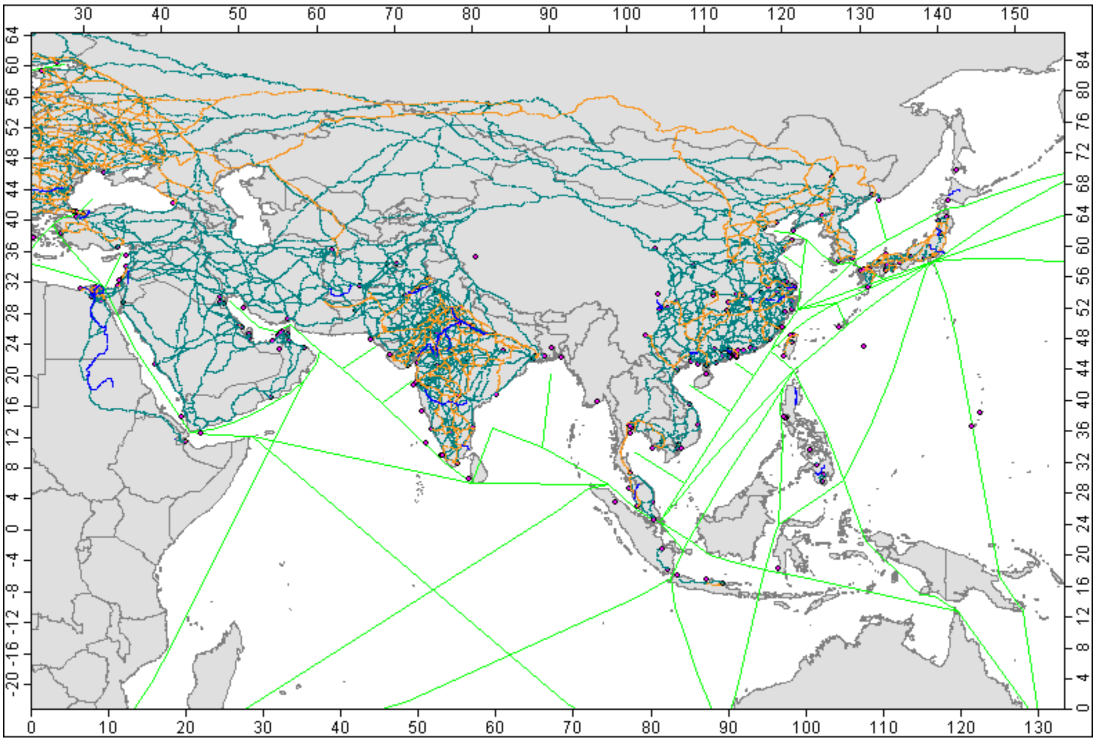

Figure 2 A global transportation network

Figure 2 depicts part of a global transportation network, including an inland transport system and a maritime transport system. Based on the global transportation network, the transport cost of any container route k equals the sum of the transport costs on each link in the route, i.e.

$$C_k = \sum_{a \in A} c_a \delta_a^k \tag{2}$$

where $\delta_a^k = 1$ if path k contains link a, and $\delta_a^k = 0$, otherwise. Any path between OD pair $w \in \overline{W}$ is regarded as "feasible" if its total transit time does not exceed the predetermined transit time constraint $\hat{T}_w$.

3. GATE PORT ALLOCATION (GPA)

3.1 A Minimization Model

Based on the global network, a methodology is proposed here to build the container route set K_w for each inland OD pair $w \in \overline{W}$ with origin node $o \in N$ and destination node $d \in N$, which is a constrained k shortest path problem. We first develop an integer programming model to obtain the container route with the lowest cost satisfying the transit time constraint for each inland OD pair $w \in W$. Let x_a, $a \in A$, be a binary decision variable indicating whether the container route with the lowest cost for inland OD pair $w \in W$ contains the arc $a \in A$. This problem can be formulated as the following integer programming model:

$$\min \sum_{a \in A} c_a x_a \tag{3}$$

subject to

$$x_a \text{ is a binary variable}, a \in A \tag{4}$$

$$\sum_{a \in A_n^+} x_a - \sum_{a \in A_n^-} x_a = \begin{cases} 1, & \text{if } n = o \\ -1, & \text{if } n = d \\ 0, & \text{otherwise} \end{cases}, \ n \in N \tag{5}$$

$$\sum_{a \in A} t_a x_a \le \hat{T}_w \tag{6}$$

where A_n^+ (A_n^-) denotes the set of all the links originating from (heading to) node $n \in N$. Eq. (5) is the conservation equation, and Eq. (6) represents the transit time constraints, where $\hat{T}_w$ is the maximal allowable transit time for OD pair $w \in W$.

The model (3)-(6) is an integer (binary) linear programming model and thus it can be solved efficiently by any integer linear programming solver, e.g., CPlex. Moreover, for different OD pairs, the shortest path problem can be simultaneously solved using different computing units. Thus, it is convenient to harness a parallel computing system to solve the shortest path problems.

After obtaining the optimal solution to model (3)-(6), which is the one with the lowest cost, denoted by $(x_a^*)_{a \in A} \in \{0,1\}^{|A|}$, the feasible path with the next lowest cost can be obtained as follows: eliminate the shortest path by adding the following constraint:

$$\sum_{a \in A^1} (1 - x_a) + \sum_{a \in A^0} x_a \ge 1 \tag{7}$$

where

$$A^1 := \{a \in A : x_a^* = 1\} \tag{8}$$

$$A^0 := \{a \in A : x_a^* = 0\} \tag{9}$$

The rest of the k_w shortest paths for OD pair $w \in W$ can be obtained accordingly by eliminating all the shortest paths previously generated.

In practice, a more efficient method can be used to solve the constrained shortest path problem: First, for each inland EQSP $n \in \bar{N}$, we can build two path sets, an inbound path set R_n^{in} and an outbound path set R_n^{out}. Each path in the inbound path set originates from an import port and ends at the inland EQSP n, while each path in the outbound path set connects the inland EQSP n to an export port. Second, for any inland OD pair $(n, m) \in W$, suppose that both n and m are inland EQSPs, then the paths from n to m can be enumerated by listing all possible combinations of path sets R_n^{out} and R_m^{in}. Suppose that one path uses the outbound path k_1 from set R_n^{out} and path k_2 from set R_m^{in}, and the export

port on k_1 is p_1 and the import port on k_2 is p_2. Then, the overall cost (time) on this path equals the sum of five portions: the transport cost (time) on path k_1; the loading cost (time) at export port p_1; the shipping cost (time) from port p_1 to p_2; the discharge cost (time) at import port p_2; and the transport cost (time) on path k_2. Accordingly, we can compare the costs of all the enumerated paths, and choose the first n_w most cost-efficient paths that fulfill the transit time constraint.

It should be noted that, if one EQSP is a sea port, then its loading port and its discharge port will be itself. When solving the shortest path problem, another hurdle is encountered; that is, since the inland transport network is built based on the historical data of the liner shipping company, some newly added inland EQSPs may be isolated from the inland network, and unconnected to any sea port by any travel mode. For instance, suppose the inland transport network of China is indicated by the road map in Figure 3. Then, the city of Jingzhou is isolated, as there is no inbound or outbound path between Jingzhou and any sea port.

Figure 3 An isolated inland EQSP

Due to the incompleteness of the historical data, the problem shown in Figure 3 will occur each time the liner shipping company expands its business and adds a new inland EQSP. To cope with this problem, another methodology is proposed in the following subsection. It provides an alternative loading/discharge port for each inland EQSP before solving the shortest path problem.

3.2 Alternative Gate Port

Based on the longitude and latitude of each EQSP (including both inland EQSPs and sea ports), we can easily obtain the distance between any two EQSPs. Let L_{ij} denote the distance between EQSPs i and j. Then, for any inland EQSP, it is quite straightforward to find the five sea ports closest to it. We denote by P_n the set of five sea ports closest to the inland EQSP $n \in \bar{N}$.

Then, for each inland OD pair $(n,m) \in W$, an alternative gate port (loading or discharge port) can be determined purely based on distance. We can enumerate all combinations of selecting one port from set P_n and one port from set P_m, and then find the path between them with the minimal cost. The cost here comprises two parts: one part based on the total distance (including distance from origin to loading port, loading port to discharge port, and discharge port to destination) and one part made up of the handling costs at the loading and discharge ports.

This alternative gate port allocation method based on distance avoids the aforementioned problem caused by incomplete transportation network data. A loading port and a discharge port will definitely be assigned to each inland OD pair. However, compared with the method presented in the section above, the results for this method are much inferior. This is because choosing the five sea ports nearest to each inland EQSP prevents the usage of any other sea ports. For example, for the inland EQSP Chicago, the five nearest sea ports are all located on the east coast of the US. Thus, any cargo coming from east or southeast Asia would be forced to use these sea ports rather than those on the west coast (say, San Pedro) which would be much more cost-efficient. Hence, after calculating alternative gate ports, the GPA problem should be modified further, using the method in the previous section based on the global transportation network.

The GPA has thus converted all the inland OD demand into port-to-port demand, and it is thus possible to employ a network design method for the seaborne liner shipping subsystem, which is introduced in the following section.

4. SHIPPING NETWORK DESIGN

4.1 Mathematical Model

The liner shipping company redesigns its liner shipping network approximately once every three to six months to cope with changes in OD demand. The network design process is usually carried out by partially adjusting the existing network, rather than redesigning the whole service from scratch. Thus, the most profitable ship routes remain unchanged; these are regarded as “compulsory” ship routes during the network design process, while the remaining ship routes and any newly added ones are taken to be “optional”. Let $\Re$ be the set of all possible ship routes, which can be divided into compulsory ship routes $\hat{R}$ and optional ship routes $\bar{R}$. Then let R denote any subset of these ship routes, forming a pattern or network, thus $R \subseteq \Re$. The target of the network design process is to find the optimal ship route pattern $R^* \subseteq \Re$, such that the operating cost is minimized.

Due to the large number of optional ship routes in $\Re$, it would be impossible to simultaneously put all of them into any solution method and obtain a global optimal solution. In fact, it is not even possible to *enumerate* all of the optional ship routes, due to the complexity of the problem. A more realistic method is to evaluate an initial ship route pattern (e.g., the current ship route network of the liner shipping company), and then gradually adjust some of its ship routes. Hence, it is important to first design an evaluation model for any ship route pattern $R \subseteq \Re$, which will give the operating cost of running this ship route pattern and also decide whether any optional ship routes in it should be eliminated.

Such an evaluation model could take the following form: Let $\mathcal{P}$ be the set of ports in the network. The total demand from port $o \in \mathcal{P}$ to port $d \in \mathcal{P}$ is denoted by q_{od}. With a little abuse of notation, we let W represent the set of port-to-port demand after GPA. Let y_{od} be the unfulfilled demand and τ_{od} be the penalty parameter for the unfulfilled demand for the port pair $(o,d) \in W$. Let N^s and A^s be the sets of nodes and arcs in the shipping network comprising the ship routes making up $R \subseteq \Re$. Note that one port may correspond to more than one node in N^s because a port may be visited more than once in a week. Let $N^s(p) \subseteq N^s$, $p \in \mathcal{P}$, be the set of nodes that represents port $p \in \mathcal{P}$. Let (m,n), $m,n \in N^s$, represent an arc in A^s. The arc set A^s consists of two mutually exclusive and collectively exhaustive sets: voyage arc A^v representing the voyage from one port to the next, and transshipment arc A^t representing the transshipment operations at a port. We further let A_r^v be the set of voyage arcs on ship route $r \in R$. Therefore, $A^v = \bigcup_{r \in R} A_r^v$ and each voyage arc $(m,n) \in A_r^v$ has a capacity denoted by Cap_{mn} that corresponds to the ship capacity deployed on ship route $r \in R$. It should be noted that different capacities reflect different vessel types. The capacity of a transshipment arc can be set to infinity. Each transshipment arc $(m,n) \in A^t$ has a cost c_{mn} and the cost of a voyage arc is 0 because the marginal cost of shipping one more container is negligible. Each ship route $r \in R$ has an operating cost c_r.

The decision variables in the network evaluation model are (i) binary decision variable x_r, $r \in \bar{R}$, which equals 1 if and only if optional ship route $r \in \bar{R}$ is used in the network, (ii) flow variable f_{mn}^v, $(m,n) \in A^s$, $v \in N^s$, indicating the total number of containers on arc $(m,n) \in A^s$ that are destined for node $v \in N^s$, (iii) the shipped containers from node $u \in N^s$ to node $v \in N^s$, represented by z_{uv}, and (iv) the unfulfilled demand y_{od} in the port pair $(o,d) \in W$. Then, the following destination-based network evaluation model is proposed:

[Network Evaluation Model]

$$\min_{x_r, f_{mn}^v, z_{uv}, y_{od}} \sum_{r \in \bar{R}} c_r x_r + \sum_{(m,n) \in A^t} c_{mn} \sum_{v \in N^s} f_{mn}^v + \sum_{(o,d) \in W} \tau_{od} y_{od} \tag{10}$$

subject to:

$$\sum_{n,(m,n) \in A^s} f_{mn}^v - \sum_{n,(n,m) \in A^s} f_{nm}^v = b_m^v, \forall m \in N^s, \forall v \in N^s \tag{11}$$

$$b_m^v = \begin{cases} -\sum_{u \in N^s} z_{uv}, \text{ if } m = v \\ z_{mv}, \text{ if } m \neq v \end{cases}, \forall m \in N^s, \forall v \in N^s \quad (12)$$

$$\sum_{v \in N^s} f_{mn}^v \leq \text{Cap}_{mn}, \forall (m,n) \in A_r^v, r \in \hat{R} \quad (13)$$

$$\sum_{v \in N^s} f_{mn}^v \leq \text{Cap}_{mn} x_r, \forall (m,n) \in A_r^v, r \in \bar{R} \quad (14)$$

$$y_{od} + \sum_{u \in N^s(o)} \sum_{v \in N^s(d)} z_{uv} = q_{od}, \forall (o,d) \in W \quad (15)$$

$$z_{uv} \geq 0, \forall u \in N^s, \forall v \in N^s \quad (16)$$

$$y_{od} \geq 0, \forall (o,d) \in W \quad (17)$$

$$x_r \in \{0,1\}, r \in \bar{R} \quad (18)$$

$$f_{mn}^v \geq 0, \forall (m,n) \in A^s, \forall v \in N^s \quad (19)$$

Eq. (10) minimizes the total cost, including the operating cost of the optional ship routes, container transshipment costs, and penalty costs for not shipping all containers. Eqs. (11) and (12) are the flow balance equations. Eq. (13) enforces the capacity constraint on compulsory ship routes. Eq. (14) enforces the capacity constraint on optional ship routes. Eq. (15) requires that the sum of unshipped and shipped containers equals the container shipment demand. Eq. (16) imposes that the number of shipped containers for each node pair is non-negative. Eq. (17) imposes that the unshipped demand for each port-to-port pair is non-negative. Eq. (18) defines x_r as binary variables and Eq. (19) defines f_{mn}^v as non-negative continuous decision variables.

The network evaluation model actually nests the container routing problem (Bell et al., 2011; Brouer et al., 2011; Song and Dong, 2012). The fleet deployment problem (Gelareh and Meng, 2010) and speed optimization problem (Psaraftis and Kontovas, 2013) can also be incorporated by copying a ship route with the same port rotation but different types of ships, or with the same port rotation and the same type of ship, but with different speeds, respectively. The network evaluation model is a mixed-integer linear programming model. Thus, it can easily be solved using existing integer linear programming solvers, e.g., CPlex. Since some optional ship routes in R are eliminated after solving the network evaluation model, for the convenience of presentation the set of remaining ship routes is denoted by R'.

4.2 Approaches for Designing New Ship Routes

Based on the evaluation results for the initial ship route pattern, two approaches are proposed for designing new ship routes: network refinement and demand recovery. The first approach focuses on those ship routes with low utilization. For example, assume that for the optional ship route depicted in Figure 4 only 10 containers are handled at the Hong Kong port, indicating extremely low utilization. Then, a new ship route is designed as follows: First, the Hong Kong port is removed from this ship route, giving Yantian - Singapore - Yantian - Pusan - Shanghai - Yantian. Second, this new ship route is set as optional and added to the current ship route set R', while the ship route shown in Figure 4 also remains optional. Then, we let the optimization model tell us which ship route to choose. Thus, new ship routes are designed by removing one or more legs with low utilization from optional ship route. If the overall utilization of a ship route is low, then a new ship route with the same port rotation is designed using smaller ships.

The second approach, demand recovery, aims to design new ship routes to fulfill unshipped demand. It should be noted that a liner shipping company may select not to transport unprofitable cargos (Agarwal and Ergun, 2008). If the volume of unshipped demand is large enough, however, a new ship route can be designed by connecting the corresponding ports. For example, we could choose the ten ports with the highest volumes of unshipped demand and determine the calling sequence for these ten ports by minimizing the round-trip journey distance. The ship type on the route is then decided based on the cumulative unshipped demand across all the ports.

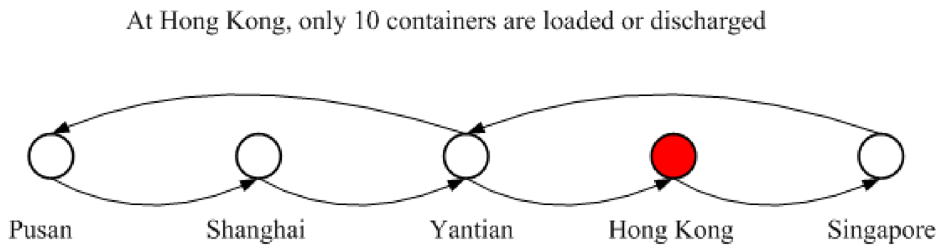

Figure 4 A ship route with low utilization

The previous two subsections have briefly introduced the methods used in maritime liner shipping network design. However, that is not the focus of this study and any of the existing methods discussed in the Introduction section of this paper could be used in place of the methods described here. Having completed the GPA and the liner shipping network design, we have a new shipping network to cope with the new demand of the liner shipping company.

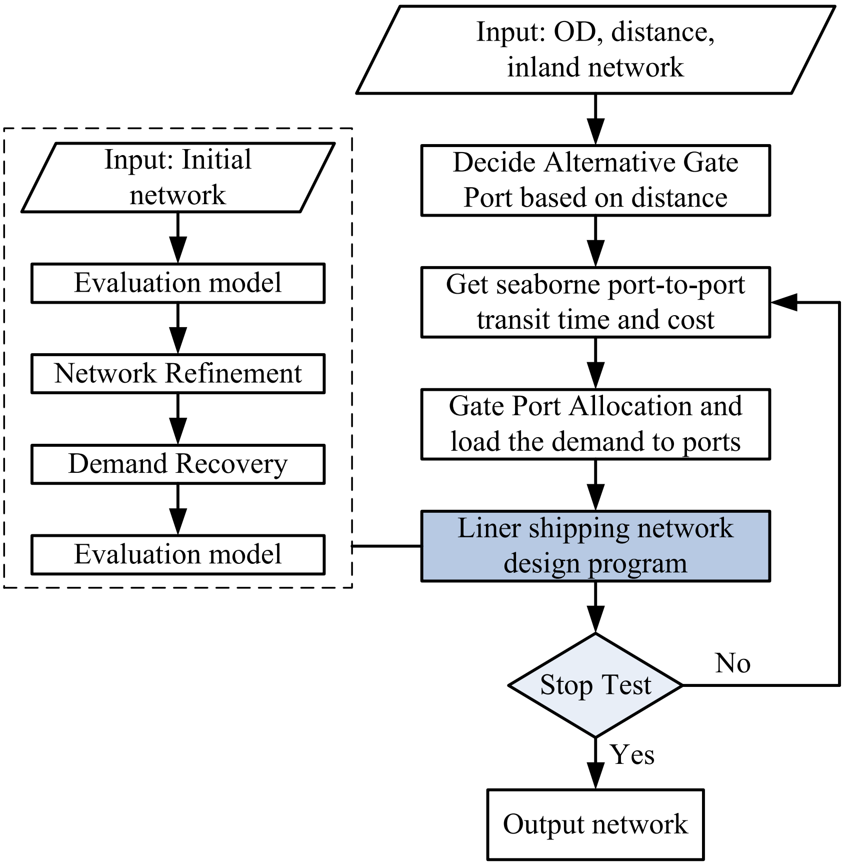

Figure 5 Flowchart of the global intermodal shipping network design

However, one flaw can be detected in the solution method: the GPA requires the seaborne transit time/cost, which is estimated based on historical data. However, after the design of the new liner shipping network, the seaborne transit time/cost will inevitably have changed. The newly designed service will thus affect the GPA. Thus, to remedy the effect of this flaw on the final results, we iteratively perform the GPA and the liner shipping network design, which gives the flowchart presented in Figure 5. The figure shows the whole procedure for the methodology proposed in this study for global intermodal liner shipping network design.

5. SOFTWARE DESIGN AND APPLICATIONS

5.1 Development Platform and Software Framework

The software tool is designed based on a simulation framework named MicroCity (MicroCity, 2013). MicroCity is a versatile, open source, and fast GIS (Geographical Information System) -type framework for studies involving transportation topics. In addition to some fundamental GIS functions, MicroCity also has many unique libraries, including Network, Fractal, 3D, Simulation and Linear Programming Solvers, making it an ideal instrument for solving the problem addressed in this paper. Moreover, it is quite convenient to use MicroCity for accessibility analyses of transportation networks, simulation in multi-agent systems and 3D real-time demonstrations of transportation systems (MicroCity, 2013).

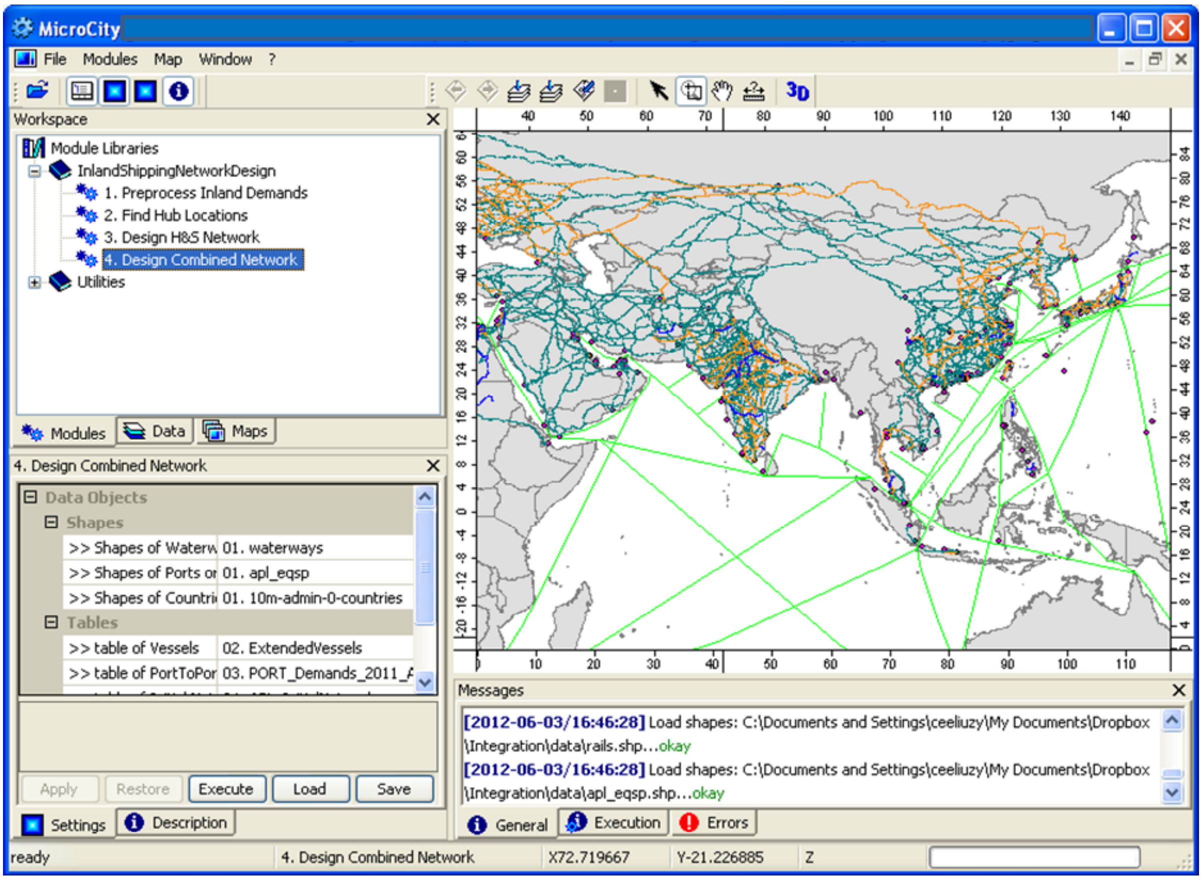

Figure 6 Graphical user interface of the software

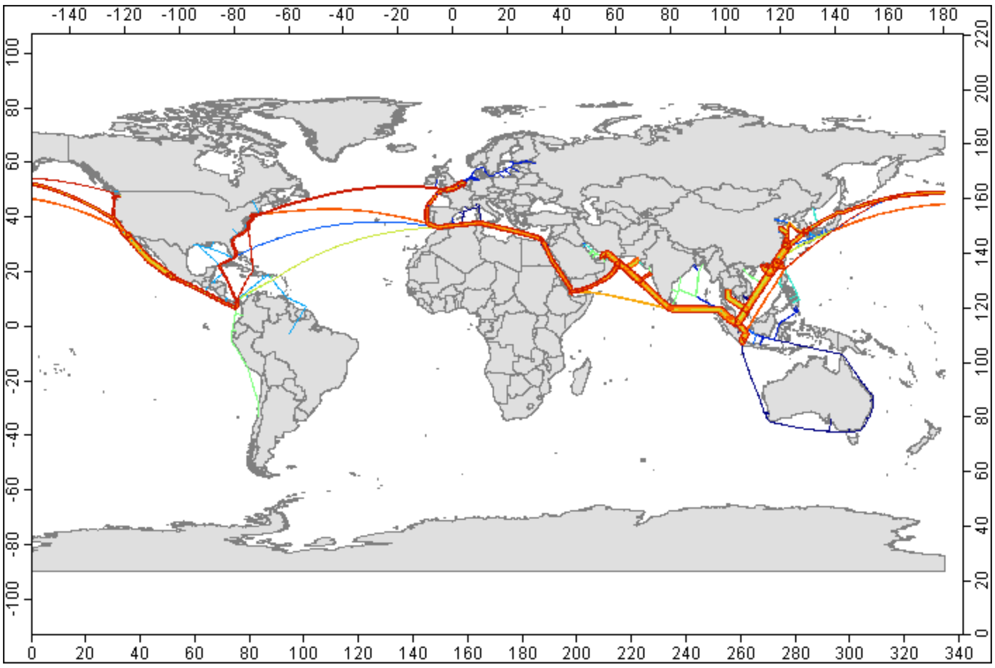

Figure 7 Resultant ship route pattern

Based on MicroCity, the software tool for global intermodal shipping network design is coded in C++ using object-oriented programming. The software tool uses a three-layer system structure: a database layer, a function layer and a graphical user interface (GUI). Figure 6 shows a snapshot of the software tool; a user-friendly GUI is provided for inputting data and viewing the resulting transportation networks. For the GPA problem, the data for the global transportation network are input from external files, and the software tool can then vividly demonstrate the spatial features of the input network, as shown in Figure 6. Based on the input database, the function layer will carry out the procedures of the solution method as summarized in Figure 5.

The outputs of this software tool mainly consist of the results of the GPA and the resulting pattern of liner ship routes. Figure 7 shows the demonstration interface for the resulting ship route pattern, with the ship routes indicated by different colors. Each ship route can then be zoomed in and targeted. The utilization of each leg of the ship routes can also be provided.

5.2 Large-Scale Application

The proposed software is applied to design the global shipping network of a global liner shipping company, representing a large-scale example of shipping network design. The network has 565 global EQSPs, including 311 ports and 254 inland EQSPs. Figure 8 shows the locations of the global EQSPs. The total container demand is more than 100,000 TEUs/week, and the total number of OD pairs is 34,742, of which 15,833 are inland OD pairs.

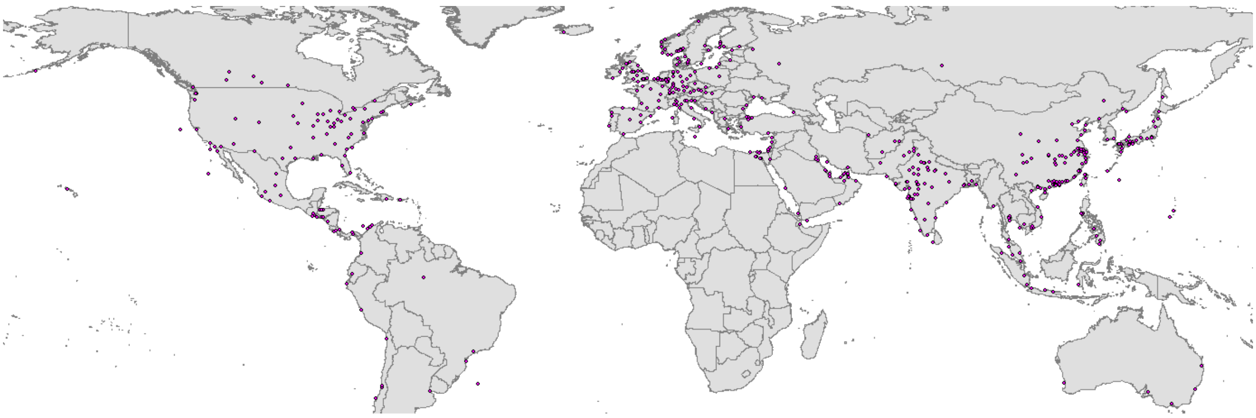

Figure 8 Global ports of the liner shipping service network

The current shipping network of the liner shipping company is taken as a benchmark to evaluate the results of the proposed network design method. As aforementioned, to cope with changed demand, instead of designing new ship routes from scratch, the liner shipping company would redesign its existing liner services by adjusting the current network. Thus, the current shipping network is taken as the initial network for the solution procedure depicted in Figure 5. Taking the shipping company's current network and the new demand as inputs for the software tool, a newly designed shipping network can be provided. Regarding the stop criterion of the iterative design shown in Figure 5, if the number of iterations is too small, it will undermine the accuracy of the results; on the other hand, if it is too large, the execution time would be unacceptably large. Based on our experimental studies, the number of iterations is taken to be 10 in this problem. The features of the initial network, as well as the resulting shipping network, are shown in Table 1.

The data in Table 1 clearly show that the newly designed network outperforms the initial/current network of the shipping company. The first column, entitled "Total Cost", is the value of the objective function (10) in the network evaluation model (unit: USD/week). The other three columns indicate the fleet size used by each network to carry the OD demand. In the initial network there are 81 ship routes, and a total fleet size of 289 ships with a total capacity of 589,460 TEUs. However, to carry the same amount of cargo, the redesigned ship network only needs 77 ship routes and 269 ships. The smaller fleet size would greatly reduce the operating costs, service costs and fuel consumption of the liner shipping company.

Table 1 The Features of Initial Network and Resultant Network

	Total Cost (USD/week)	**No. of Ship Routes**	**Total No. of Ships Used**	**Total Ship Board Capacity** (TEU)
Initial Network	49756200	81	289	589460
Resultant Network	45556200	77	269	529460

The other type of output from the software tool is the conversion of inland OD demand to port-to-port demand. For the liner shipping company, more than half of the OD pairs are inland OD pairs. Thus, it is necessary to carry out GPA for these inland OD pairs. Among the 15,833 such pairs, 191 have an origin and/or destination isolated from the transportation network. Thus, it is necessary to conduct the alternative gate port allocation procedure first. The final results show that, after GPA, the total number of OD pairs shrinks from 34,742 to 19,672.

To illustrate, one inland EQSP, Chicago, is selected. The total outbound volume from Chicago is 1,630 TEU/week to 137 different destinations. As shown in Figure 9, all of these containers are handled at one of three loading ports: San Pedro in the west; New Orleans in the south; and New York in the east. Note that, since the inland transportation costs are much higher than the seaborne costs, all other loading ports are dominated by these three. For example, there are other ports on the east coast of the US, including Boston, Charleston, Savannah, Jacksonville and Miami. However, the inland transportation costs from Chicago to these ports are much higher than that to New York. Therefore, even though lower seaborne costs could be achieved between Chicago and destinations in South America by using, say, Miami as the loading port, the overall cost is still minimized by taking New York as the export port. This example shows the tradeoff between inland and seaborne costs, and also verifies the necessity of the holistic analysis used in this study for intermodal liner shipping network design.

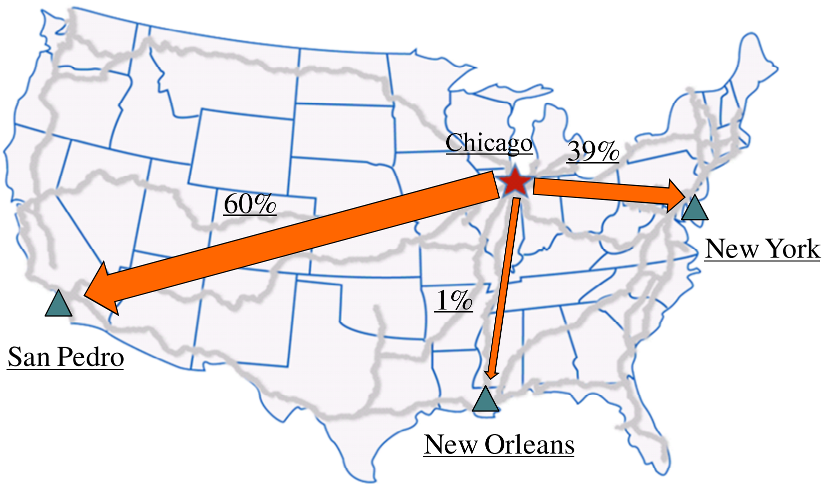

Figure 9 Allocation of outbound demand from Chicago

6. CONCLUSIONS

This paper has focused on the network design of a global intermodal shipping system that includes an inland transportation subsystem and a seaborne liner shipping subsystem. As mentioned at the end of the Introduction section, this problem is still an open issue in the literature, and its solution will evidently affect the operating costs of any liner shipping company. Yet, the problem is inherently complex and is strongly NP-hard. This paper therefore proposed a holistic methodology. In view of its practical significance, a software framework was also presented, based on the proposed methodology. A large-scale application based on a real-life case of the global network of a liner shipping company was then adopted to verify the model and the software.

The numerical results showed that the network designed by the software tool was superior to the existing network of the liner shipping company. The numerical example also indicated that inland transportation would evidently affect the itinerary used for cargo shipment, implying that the inland aspect should not be neglected in liner shipping network design. More effort is needed to extend the work presented in this paper by considering some of the practical features of the liner shipping business. First, in this paper the demand between each OD pair is assumed fixed, yet in practice it is affected by the total shipping charge. Thus, demand elasticity should also be addressed in future work. Second, container terminal operations such as the availability of berths (Du et al., 2011; Imai et al., 2013), which affects the arrival and departure time of ships at each port of call (Qi and Song, 2012), may also be incorporated in modeling. Third, there are a number of uncertainties associated with liner shipping operations (Notteboom, 2006; Yan et al., 2009; Brouer et al., 2013). How to consider these operational-level uncertainties in tactical-planning network design models is a worthwhile research topic.

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